

Investigation of the feasibility of a Superconducting “self-healing” DC Grid on a LNG Carrier

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Abstract— The purpose of this work is to investigate the implementation of superconducting (SC) Direct Current Power Distribution on the power grid of a LNG Carrier. In the first part of the paper, the state of the art in High Temperature Superconductor technology is reviewed and an analytical approach of Superconducting DC Power Distribution on a power system is provided. In the second part, a simulation of a SC distribution line is performed during the transmission from superconducting to normal state regarding power losses and the operation of the line as a fault current limiter..

Index Terms—All-Electric Ship, DC Distribution, High Temperature Superconductors.

I. INTRODUCTION

During recent years, the usage of electrical power on-board vessels has grown exponentially. This fact, led researchers to consider new versatile and more efficient power distribution architectures that support the operational needs of these new loads. The widespread electrification of systems that have been coupled to AC electric network via frequency converters and the large-scale usage of cryogenics on Liquefied Natural Gas (LNG) Carriers has evolved to the recognition of the favorable characteristics of the Superconducting Direct Current (DC) grid. When carrying DC current superconductors are perfectly lossless regardless of the cable length and the power rating of the line [1]. Also, superconducting elements due to their nature can act as fault current limiters. During normal operation the system operates without any limitations because the resistance of the superconducting element is essentially zero, and it is possible to minimize the inductive impedance. However, during a fault when the fault current reaches many times the rated value, the superconducting element reverts rapidly to its normal state (i.e., its resistance increases to a defined value). The increased resistance/impedance limits the fault current to the desired level. The major goal of this paper is to investigate if the implementation of a DC superconducting line in the power distribution network has the benefits that were presented above.

II. HIGH TEMPERATURE SUPERCONDUCTORS

The benefits of superconducting grid technology are now within reach. Since the end of the 80's, enormous progress have been made to discover and develop materials that are superconducting above the temperature of boiling liquid nitrogen; designing scalable manufacturing routes that promote dual axis alignment and vortex pinning needed for high-current operation; and designing and demonstrating cables, transformers, fault current limiters, and rotating machines.

First-generation superconducting wire based on bismuth strontium calcium copper oxide (BSCCO) has been surpassed by second-generation (2G) wire based on YBCO, with a radically different architecture and much higher performance potential. This paradigm shift in materials and design has enabled rapid progress in the last five years, increasing current-carrying capability by a factor of 10 and length by a factor of 1,000.

Superconductivity provides novel solutions for increasing grid capacity and reliability, while dramatically improving efficiency as well. Superconducting wires carry up to five times the current of copper wires that have the same cross section. Superconducting generators cut electrical generation losses in half, reduce volume and weight by a factor of two, and are stable against voltage and reactive power fluctuations. Superconducting transformers cut weight and footprint by a factor of two, cut losses by a factor of two, and uses no contaminating or flammable cooling oil that could limit their use in urban areas. Superconducting fault current limiters are smart, fast switches that react abruptly to an overload current, limiting its magnitude and preventing damage to the grid; when the fault is cleared, they reset quickly, restoring the grid to full operating capacity[2].

III. CRYOGENIC SUPPORTING TECHNOLOGY

LNG Carriers are a special type of marine vessels that are used for the transportation of Liquefied Natural Gas to long distances. Since natural gas liquefies at cryogenic temperatures, i.e. temperatures well below -100°C, these

vessels are equipped with state of the art compressors and cryocoolers which make them appealing for integrating superconducting distribution lines. A very big portion of the installation cost of a SC line is the cryogenic technology. However if such installation is already present then there are much fewer modifications that need to be made at the vessel. These modifications include but are not limited to vacuum-jacketed cable cryostats for the HTS devices and new insulation materials for the cryogenic temperatures. It is particularly important for these materials to have high thermal conductivity and low electrical conductivity to allow for rapid heat removal to achieve stability or to allow for the quick introduction of heat to achieve quench protection. It may also be possible to design insulation that switches from insulating to conducting with a rise in temperature to achieve quench protection[7].

IV. SUPERCONDUCTING DC DISTRIBUTION CABLE MODEL

A. Background

The Finite Element Analysis (FEA) Method is a numerical method which is used for the solution of physical problems that are described by complex state space equations. In the particular case that the general state-space equation has the form of a composite differential equation with almost infinite freedom degrees, the numerical solution requires a lot of time and computational resources. The basic idea of the FEA method is the division of a total workspace Ω , to many areas, which can then be described by simpler state space equations. The discrete model that comes out of the division mentioned above can be approximated by segments of partially continuous state space equations that have finite number of freedom degrees. The decrease of the model's freedom degrees significantly accelerates the solution of the system.

B. Modeling a High Temperature Superconducting Cable

One of the most appealing characteristics of the High Temperature Superconducting cables is that potentially they can have zero losses during their operation. Also because of their highly non-linear Voltage-Current characteristics, superconductors can act as "smart switches" rapidly converting from zero to finite resistance as the current exceeds a critical value[3]. As a result of the above, modeling a system like that with Finite Element Analysis tools is particularly useful to determine grid operation and loss prediction in energy applications. The major tackle for the simulation is the non-linear resistance characteristics of the superconducting materials. This means that the modeling cannot be accurate with the pre-defined tools that exist in most simulation software but must be studied as a transient phenomenon of a material that changes properties during time.

The superconducting materials, in contrast to common materials that have a constant special resistance ρ , can be modeled using a special non-linear resistance[1],[3]. The value of this resistance is relevant to the conductor's current density J . The formula that defines the special resistance of

the superconducting materials is empirical and is given below in equation (1) :

$$\rho(J) = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1}$$

where J_c is the critical current density and has values around $10^8 - 10^{10} \frac{A}{m^2}$ and $E_c \approx 10^{-4} \frac{V}{m}$ is the intensity of the electric field when the current density approaches the critical value J_c . The value of the exponent n is 25-50, derives from experimental data and describes the speed of transition from superconducting to normal state [5]. In general the superconducting cables are characterized by anisotropy. Both the critical current and the exponent values depend on the angle θ of the cable with vector \vec{B} of the magnetic induction. However, for simulation reasons, at this work the above parameters θ, \vec{B} will be considered isotropic and with constant value. As initial conditions the intensity of the magnetic field H is assumed to be zero in order to assure that the solution of the equation $H(t)=0, t>0$ is unique. In the two dimensional model that was created, the size of cable against z axis was considered to be infinite. This approximation is accurate for most of the designs of superconducting cables and tapes. The Maxwell equation for the problem – eq. (2), can be expressed as a function of the two components of the intensity of the magnetic field at x and y axis, i.e. H_x, H_y .

$$\nabla \times H = J \Rightarrow J_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}$$

In two dimensions, equation (2) above is scalar and can be simplified to the following expression:

$$J_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \quad (3)$$

According to (3), the special resistance of the superconducting cable that was described with eq. (1) can be expressed as a function of the intensity of the magnetic field as :

$$\rho(J) = \frac{E_c}{J_c} \left| \frac{\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}}{J_c} \right|^{n-1} \quad (4)$$

with initial conditions $H|_{t=0} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$.

A SC cable has practically zero electric resistance in DC currents, if the temperature level, the current and magnetic field densities are below the critical values. The current model solves the time variant problem of a sudden current injection in the conductor which is close to the critical current density [6]. This sudden current rise could be a fault at the superconducting distribution line.

C. Definitions and Assumptios

The correlation between the electric resistance of the SC cable and the current density makes the solution with the ordinary magnetic field equations difficult. This is due to the fact that the special resistance of the superconductor is dependent on itself in a cyclical manner [1], [4]. So in this

paper an alternative approach was employed, where the magnetic field is used as the dependent variable. The current density derives from eq. (3) and the Faraday law defines the whole system based on equation (5) below:

$$\nabla \times E(J) = -\mu \frac{\partial H}{\partial t} \quad (5)$$

The intensity of the electric field E depends on the current density and it is expressed according to the empirical formula:

$$E(J) = \begin{cases} 0, & |J| < J_c \\ E_0 \left(\frac{|J| - J_c}{J_c} \right)^a \frac{J}{|J|}, & |J| > J_c \end{cases} \quad (6)$$

It is obvious that the intensity of the electric field is zero during the superconducting state. The parameters E_0 , a are constants that define the non-linear behavior of the transition from superconducting to normal state. J_c is the critical current density that is decreasing with the rise of temperature. For the simulated superconducting cable the material YBCO was used which has the parameters that are presented in table 1 below [4], [8]. The numerical simulation results were based on solving the Maxwell equations. In the 2D model that was simulated, only the dimensions on x and y planes were considered while the length of the cable was assumed to be infinite. Equation systems with two vortex operators are more efficiently solved by using vector elements. The finite element analysis method that was used includes vector elements for the solution of similar equations. The total was based on the following partial differential equation with dependent variables the H_x and H_y components and D_a the damping coefficient of the field.

$$\begin{aligned} D_a \frac{dH}{dt} + \nabla \cdot \Gamma &= F \\ \Rightarrow \begin{bmatrix} \mu_0 & 0 \\ 0 & \mu_0 \end{bmatrix} \cdot \begin{bmatrix} \frac{dH_x}{dt} \\ \frac{dH_y}{dt} \end{bmatrix} \\ + \nabla \begin{bmatrix} 0 & E_z \cdot (J_z) \\ E_z \cdot (J_z) & 0 \end{bmatrix} &= \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \end{aligned}$$

For symmetry reasons it was assumed that the current's only component is through the z axis. The current that runs at the superconducting line is limited by the outer boundary conditions of the problem. Assuming cylindrical symmetry according to Ampere's law the current will be:

$$\oint \mathbf{H} d\mathbf{l} = 2\pi r H_\phi = I_{wire} \Rightarrow H_\phi = \frac{I_{wire}}{2\pi r} \quad (8)$$

The model consists of two homocentric cross sections. The SC cable has radius of 0.1m and is from YBCO. The second and larger cylinder section has the properties of air. The exact model is depicted in figure 1. For the solution of the system's equation the parameters that were used are these of Table 1. As was stated before, the phenomenon under study is time variant, and a step time $T_s = 0.005$ s was chosen. The current

that flows through the cable can be described with equation (9) below.

$$I = I_0 \left(1 - e^{-\frac{t}{t_0}} \right) \quad (9)$$

The current density was expressed as a function of x and y components of the magnetic field intensity according to equation (3). The heat per unit of volume Q , that is developed in the interior of the superconductor is described from:

$$Q = E_z J_z \quad (10)$$

The intensity of the electric field change E_z is defined differently at the two regions of the problem. In the outer region (air) that surrounds the cable is: $E_z = \rho_{0air} J_z$ (11). At the region of the cable that is in superconducting state the electric field is zero, while in the area of the superconductor that the current density is above the critical value, the electric field that is created can be calculated from equation (6) above. In the boundaries of the problem, the Dirichlet condition was defined for the intensity of the magnetic field.

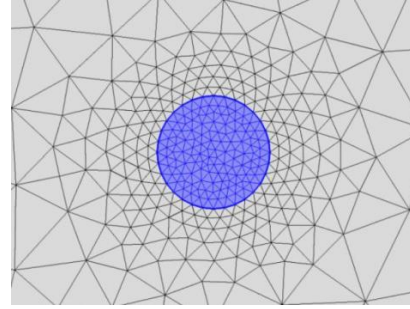


Figure 1 : Model of The SC DC Distribution Cable

As a result, in a cylindrical system of coordinates the magnetic field will have a component in the direction of the angle ϕ which is calculated as :

$$H_\phi = \frac{I}{2\pi\sqrt{x^2 + y^2}} \quad (12)$$

Parameter Name	YBCO Parameters
	Values
E_0	0.0836168 V/m
a	1.449621256
J_c	1.7×10^7 A/m ²
T_c	92 K
I_0	10^6 A
$\rho_{0 air}$	10^6 Ohm \times m
t_0	0.02 s
dT	4 K
dJ	1700 A/m ²

Table 1: Parameters of the Superconducting Material YBCO

D. Simulation and Results

In the simulated model, a fault current is injected at the cable in logarithmic scale with step of 0.02sec until it reaches a

final value of IMA. The Finite Element Analysis method that was used is efficient for modeling of materials that present non-linear relationship between electric field and current density (figure 2). This non-linear relationship is expressed as an electric resistance that depends on current according to equation (13). The electric field is zero for values of current density below the critical as it was discussed above. This is a specific property of superconductors.

$$J = \sigma E \Rightarrow \rho(J) = \frac{E}{J} \quad (13)$$

The simulation results, present the variation of the material's critical parameters at its total surface and the screenshots that are imprinted are between $t=0$ and $t=1$ seconds. Figure 2 below depicts the spatial distribution of current density for the time moments 0.005, 0.02, 0.05 and 0.1 seconds.

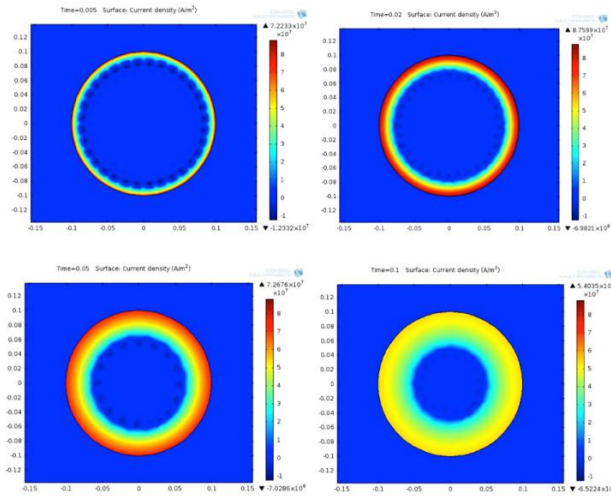


Figure 2: Alteration of Current Density (J) during a fault at the SC Cable

- For $t=0.005s$ there is exclusively peripheral current flow, as the current density is defined by the London Theorem[reference] regarding a material that is in superconducting state. The current density in a superconductor can be expressed as: $J = \frac{H_0}{\mu} e^{-\frac{x}{\mu}}$ (14) [9], where μ is a constant called London Penetration depth and is relevant to the type of the material and x is the distance of a point from the superconductor's perimeter. H_0 is the intensity of the outer magnetic field. From eq. (14) it can be observed that for x values that are bigger than the penetration depth, current density is exponentially decreased towards the inner areas of the superconductor. The maximum value of density is

$J_{max} = 7.2333 \times 10^7 A/m^2$, significantly bigger than J_c . This causes the transition of the surface from superconducting to normal state.

- For $t=0.02s$ appears the maximum current density of the problem. This is due to the increase of the fault current at the conductor. This maximum value appears at the perimeter of the cable, while in areas closer to the center current of lower density is starting to appear.
- For $t=0.05$ and $t=0.1$, the phenomenon of the transition to normal state is evolving. Current flows through the areas that are closer to the center of the conductor which indicates that the material is switching to normal state.

At figure 3 below, the intensity of the Electric field E is depicted both in the air that surrounds the superconducting cable and at the conductor itself. The equations that describe the Electric field were discussed above. From figure 4, it can be deduced that the electric field is rapidly decreasing over time meaning that the cable is starting to lose its superconducting properties after fault initiation.

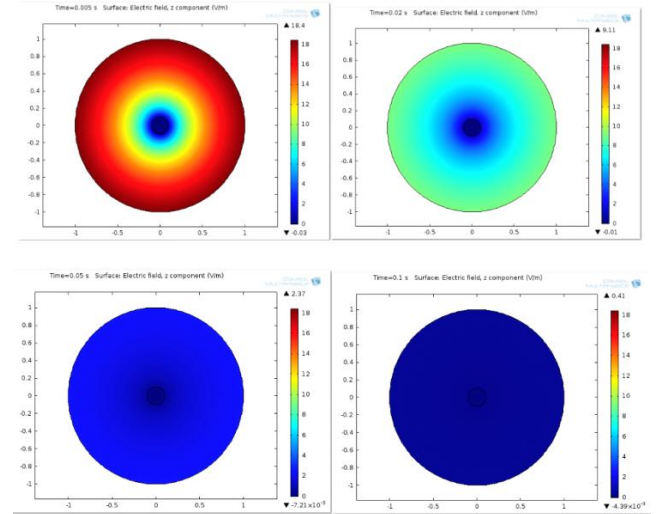


Figure 3: Alteration of the Intensity of the Electric Field (E) during a fault at the SC Cable

Figure 4, shows the distribution of thermal losses Q per volume unit that are developed in the conductor during the fault. According to equation (10) above, the losses are equal to the product of the components of Electric intensity and the density of current. During the superconducting state the losses are almost zero. After

fault initiation, the maximum value of losses is $Q = 5.7708 \times 10^7 \text{ W/m}^3$ ($t=0.02\text{s}$). It can be observed that the amount of losses is directly proportional to current density, both quantitatively as values and also qualitatively as spatial distribution in the inner areas of the cable.

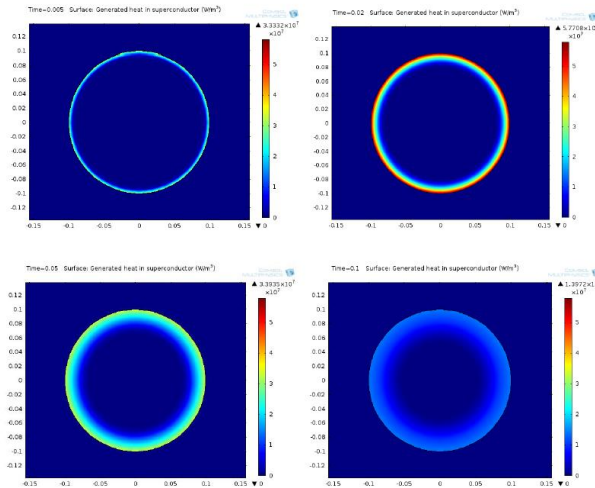


Figure 4: Thermal losses per volume unit during a fault at the SC Cable

Finally, a qualitative approach of the results is in Figure 5. As the induced current at the cable becomes higher the material starts to lose the superconducting properties and gradually becomes an insulator. The transition becomes in less than 0.3 seconds with direction towards the center of the cable.

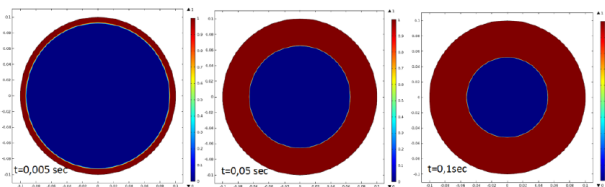


Figure 5: Transition from superconducting to normal state during the fault

V. CONCLUSIONS AND RESULTS

In this paper, the theory of superconductivity regarding DC distribution cables was presented and a SC line from YBCO was modeled and simulated. The simulation results show that for energy applications and especially for a marine installation such as a LNG carrier where a cryogenic

installation is available, a superconducting line presents no losses during normal operation and acts as a natural fault current limiter in presence of high currents. However, for installations that require high currents to operate, the design and the choice of the material could be more complicated. A basic requirement for the selection of a superconductor should be the critical current density and the critical temperature in which the material can maintain its abilities. Future work includes further deepening on applications of superconductivity for marine applications such as the expansion of current model to 3D and the comparison of superconducting DC and AC cables. Also, the installation and maintenance cost of SC lines will be examined.

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